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HIGHWAY CENTER-BARRIER INVESTIGATION
Part II. Model Study

by

James A. Starrett

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STEVENS INSTITUTE OF TECHNOLOGY
CASTLE POINT STATION
HOBOKEN, NEW JERSEY

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I Robert Ehrlich

I. Robert Ehrlich, Manager
Transportation Research Group

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ABSTRACT

This study was conducted to examine the use of models in investigating the acute-angle impact of motor vehicles on rigid, non-yielding concrete barriers with sloping faces.

Although qualitative correlation and some useful results were achieved, the model simulation could not be quantitatively validated because of insufficient full-scale data.

A complete description of the model and the test setup is presented, as well as a detailed analysis of the relationships required between the model and the full-scale prototype.

INDEXING KEYWORDS

Highway Safety
Motor Vehicle Simulation
Impact Modeling
Center Barriers
Guard Rails

TABLE OF CONTENTS

NOMENCLATURE

a	acceleration
c	damping coefficient
F	force
f	frequency of oscillation
g	acceleration of gravity
I	moment of inertia
k	spring rate
ℓ	length
M	mass
N	weight of normal load on tire
t	time
V	velocity
W	weight
δ	deflection of tire
λ	scale factor
$(\ )_m$	property of model
$(\ )_p$	property of prototype (full-size vehicle)

INTRODUCTION

In recent years, and especially since the advent of high-speed travel, there has developed an increased emphasis on efforts to prevent vehicles on highways from crossing over into opposing lanes of traffic. There are two general methods of prevention. One method, applicable in new road construction when the land is available, is to leave generous safety zones between opposing roadways, so that vehicles which are out of control can roll safely to a stop or be returned to control while separated from the main stream of traffic. The other method is to use physical restraints such as guard rails or barriers.

Two such physical restraints are the non-yielding concrete wall and the massive steel barrier. Barriers of this kind are found either as dividers between opposing lanes of traffic or as bridge parapets. They can prevent vehicle penetration, but the effect on the vehicle and its occupants is often disastrous.

Another method of restraint, when space is adequate, is the use of a deformable barrier (which gradually absorbs the kinetic energy of the vehicle) to stop or deflect the vehicle with a minimum amount of damage to the vehicle and its occupants. This type of barrier usually consists of energy-absorbing steel rails, ribbons, or wire rope which convert kinetic energy into elastic deformation, friction, and heat. Experiments have also been conducted recently with shrubbery or bushes which entrap the vehicle and slow it down without excessive damage to the vehicle or its occupants.[1]

While the concrete wall or massive steel rail certainly should contain the vehicle, it can provide protection for the occupants of a stray automobile only if it is properly designed to deflect rather than to stop the vehicle. The deformable barriers, although they protect the occupants of an automobile, require space in which to deform without interfering with opposing traffic. They also must be properly designed to prevent the "pocketing" of the errant car at a barrier support-post.

Frequently, wide center malls or deformable barriers are not practicable for use in the separation of opposing lanes of traffic on existing highways, because of roadside developments and other features of local environment. Such a situation calls for a non-yielding barrier of minimum cross section which will redirect the vehicle back into its proper lane with minimum damage to the vehicle and its occupants. This study is concerned with scale-model investigations of such barriers, especially the study of the vehicle-barrier impact phenomenon at low (less than 15-degree) angles of impact.

Several scale-model vehicles were built which incorporated those elements of a full-size automobile which were considered to be significant to the vehicle-barrier impact. These models were then projected against similarly scaled barriers to study the vehicle-barrier interaction. Plans to validate the model called for a comparison of the model-test results with results of similar full-scale tests conducted by other agencies. It was originally hoped that after model validation many barrier designs could be conceived and tested to optimize the desired safety features.

Although the study described herein was directed toward investigation of a highway center barrier, most of the information is also applicable to roadside restraining devices such as bridge parapets or guard rails.

The report is Part II of a two-part study of the center barrier. Part I, Davidson Laboratory Report 1138 sub-titled "Accident Analysis," is concerned with a statistical study of the effects of center-barrier installation on traffic safety.

MODEL DESIGN

THE VEHICLE MODEL

While prototype data were being accumulated, and in order to check out the test equipment and to ascertain the degree of sophistication required for a proper vehicle model, three progressively more complex vehicle models were constructed. All models, including barrier models, were constructed to a 1/8 scale (λ=8).

Rigid Model

A rigid model (Fig. 1), with solid axles and backbone, was designed and used to check the catapult, timer, lights, and camera setup. Since there was no springing or damping in this model, the runs against the barrier showed unrealistically abrupt changes in roll and pitch, in addition to the expected changes in heading. The only yielding members were the tires, which caused the vehicle to bounce excessively. When one tire struck the barrier and was lifted by the impact, other tires were also lifted off the ground, because of the fixed relationship of the wheels. Model simulation was of course inadequate, but the model served its purpose of checking out test equipment.

Semi-suspended Model

This model is shown in Figure 2. A joint was put into the rigid model between the axles and the backbone. Springs were added to control axle movement, and friction clutches were mounted to provide damping. The overall rotation of the axles about the roll axis was limited by rubber bump stops. Because of these features, the wheels of this model had a more flexible pattern of motion, which during impact allowed the vehicle to make simultaneous contact with the road surface and the barrier. The vertical-impact reaction was still transmitted directly through the bearings to the backbone of the model, instead of through the spring-shock arrangement

usually found on an automobile. The gross motions of the model were similar to those of the prototype, but model simulation was not yet considered satisfactory.

Fully Suspended Model

This final model is shown in Figure 3. To obtain more dynamic correlation, this model was constructed with a complete suspension system. It had independent A-arm front suspension with a geometrical configuration which ensured that the point of contact between tire and road would move up and down in a straight line, thus reducing sideward scuffing. The model originally was equipped with torsion bars instead of front springs, to simplify construction and spring-rate adjustment. However, the shear stress in these torsion rods was excessive, and they were replaced with coil springs concentric with the front shock absorbers. This method of springing does not allow for easy adjustment of the spring rate, but worked well after final adjustment.

Each front wheel was equipped with an independent shock absorber (Fig. 4). This was a double-acting hydraulic shock absorber with different compression and rebound characteristics. A more detailed description of it appears on pages 7-9, and it is shown in Figure 5.

The rear-end suspension system consisted of a solid axle which was free to rotate about the roll axis and also free to move up and down about the pitch axis. Thus each wheel had an up-and-down motion similar to that of a wheel on an automotive vehicle with conventional rear suspension -- the motion in this case being made possible by a ball-joint attachment between the axle and a point toward the center of the chassis. The axle was restrained from sideward motion by a panard rod fastened between the left side of the chassis and the right side of the axle. Coil springs on each side of the rear axle provided proper spring rate, and two shock absorbers (similar to those used on the front suspension) provided damping.

Rubber bump stops limited the compression and rebound on the front wheels, and the compression (only) on the rear wheels. Rear rebound was limited by a small wire rope which stopped extension of the coil springs and protected the shock absorber against breakage.

To scale the weight of the model properly, lead weights were attached to the chassis in positions determined by the center-of-gravity and pitch-moment-of-inertia data supplied by the manufacturers of the prototype vehicle. These weights appear in Figure 3 as two lumped masses almost directly over each axle, centered about the roll axis. No information on prototype roll and yaw moments of inertia was obtainable during the course of this study; hence they were not modeled.

The model rolled on four wheels, each consisting of a rim that rotated on an inner and an outer bearing and a tire which was mounted to the rim. The tire was made from polyurethane foam and coated with a rubber-base paint. The best available material yielded a tire which had a load-deflection rate about twice that desired. Since the coefficient of friction was correct, it was decided to proceed with this tire and to investigate the tire problem further at a later date.

The remaining appendages on the model were designed to protect the model from damage after it impacted against the barrier. A bumper which did not contact the barrier at low angles of impact served to absorb the impact as the model was decelerated at the end of each run. A roll-bar was attached at front and rear to protect the shock absorbers and their mounting brackets in the event the model did not land right side up. These roll-bars also served to trip the speed timer.

THE BARRIER MODELS

The model barriers were cast in concrete in proportions scaled to the prototypes or full-size barriers they represented. Surfaces were made as smooth as possible. It is not believed that the surface has a major effect on model reaction.*

*Tests conducted by General Motors with barriers of various surfaces indicated that changes in friction coefficient did not noticeably change the action of the vehicle as it was redirected away from the barrier.[2]

The New Jersey Concrete Barrier

The modified New Jersey Concrete Barrier consists of a three-slope wall which is cast in place (Fig. 6 shows scaled model).

The first slope, or face, consists of a 3-inch vertical section similar to a curb, which redirects the wheel of the vehicle at very low speeds and low impact angles. Because of today's high-speed traffic, this curb has little effect; it serves chiefly as a means of convenient transition from barrier to road surface, and as a means of allowing for the increase in the height of the road surface which may result from resurfacing (the curb then prevents impingement on the angled face of the barrier).

The second slope is angled away from the road at 35 degrees from the vertical and is designed to redirect the front wheel at slightly higher speeds and to return the vehicle to the desired direction of travel. It starts at the top of the 3-inch curb and continues to a height of 10 inches. This second slope also ensures against contact between barrier and vehicle sheet-metal, at near 0-degree impact.

The third slope is 6 degrees from the vertical and functions as a near wall in cases where the vehicle mounts the 35-degree slope. This section of the barrier is meant to contain and redirect the vehicle at high speeds and larger angles of impact. The over-all height of the barrier modeled was 32 inches (full scale).

The General Motors Barrier

The General Motors barrier is similar to the New Jersey barrier, with the following four minor differences (see Fig. 7, showing scaled model):

The lower face or curb is only 2 inches high.

The second face is at the same 35-degree angle from the vertical, but it extends to a height of 13 inches.

The uppermost face is sloped almost 10 degrees from the vertical.

The two upper faces meet at an abrupt angle; they do not meet in a rounded radius as in the New Jersey barrier.

PROTOTYPE DATA

After considerable investigation, the usable data available for the prototype were found to consist of one high-speed movie sequence[3] taken by the General Motors Corporation during tests conducted at their Milford Proving Grounds in Michigan. These tests were conducted with a 1964 Chevrolet Impala, impacting a GM barrier installed on a dirt surface at an estimated speed of 50 miles per hour (mph) and at an estimated 12-degree angle. A conventional-speed color panning view of the impact was also available, but was not usable in data analysis.

Information on all the physical characteristics of this test-automobile was requested from General Motors, so that those engaged in the study could proceed with validation studies of the model. Unfortunately, complete information and specifications for the prototype were not received until after completion of the study. Separate sources yielded basic data on tire characteristics, shock-absorber curves, etc., but vital modeling information such as centers of gravity, moments of inertia, unsprung mass, body twisting, etc., was not available. Since time and funds were limited, the investigators were forced to use a set of "parameters for typical 1964 low-price full-size four-door sedans" supplied by the General Motors Corporation. This set of data was supplemented by information on tires provided by the United States Rubber Company and by data on shock absorbers provided by the Monroe Auto Equipment Company. The model therefore took on the characteristics of a "typical" vehicle and was not a true scale model of the vehicle tested by the General Motors Corporation.

MODEL SUSPENSION SYSTEM

Early preliminary tests indicated that the suspension system was a critical part of the model vehicle. Considerable effort was therefore devoted to proper modeling of the system, especially of the shock absorbers.

There is no doubt that shock absorbers are essential to vehicle performance, but it is difficult to determine what degree of accuracy is necessary to achieve reliable results in impact tests. On the second (semi-suspended) model, friction dampers were used to determine whether some form

of damping was necessary. It was found that these improved the performance of the model considerably, but there was still a question as to how much effect the static friction had on model rebound and hence on final trajectory.

The third (fully suspended) model was conceived to simulate the vehicle more closely. Realistic shock absorbers were considered essential for proper model behavior during and after barrier contact.

A closed dash-pot was considered the best method of damping, for the same reasons it is used in full-size vehicles. The problem was to secure a compact, lightweight damper which was liquid-tight and fairly rugged. Also, it had to comply (when properly scaled) with shock-absorber specifications for damping force and friction.

Most "off the shelf" damping units were not suitable for one or more reasons: they were too large, too heavy, in the wrong force range, or too fragile for this application. Double-acting pneumatic and hydraulic cylinders were considered and several sample units were purchased. Most of these units were designed for high-pressure operation and showed considerable static and sliding friction. After substantial effort, it became evident that a shock absorber of suitable design (for modeling purposes) was not commercially available. Since model fabrication was being delayed while the search for the shock absorbers continued, an experimental shock absorber was built along simple lines and tested.

The first design was a tube with a cap and seal at each end. Since a single rod and piston would give a volume change as the piston was advanced into the cylinder, the rod was allowed to extend through both ends of the cylinder. This design allowed construction of a closed unit without a reservoir. Fluid viscosity was varied to obtain changes in damping. A Dow Corning silicone oil was used, because its viscosity did not change with changes in temperature. The unit was oscillated while force measurements were taken and recorded; the data were then compared with full-size damping curves obtained from the Monroe Auto Equipment Company and were used to design the four shocks to be used on the suspended model.

As the piston moves in the cylinder, the oil passes around the piston through the clearance provided between the piston and wall, producing

a nozzle effect. The force curves obtained with the unit were similar to those of prototype shock absorbers of similar design. To obtain different forces in compression and rebound, the piston was provided with several ports and flapper valves, to reduce the force on the compression stroke.

Although the constant-force type of shock was used on the prototype vehicle, the orifice type was used on the model because it was easier to construct in the initial phases. This meant that a slightly higher force would be transmitted to the chassis during impact, and may account for some of the exaggerated model behavior.

Typical values for the shock-absorber forces are 0.694 lb on rebound (FS = 355 lb)* and 0.284 lb on compression (FS = 145 lb) for constant-force or blow-off shock absorbers. The forces on the orifice shock absorbers reach 1.465 lb on rebound (FS = 750 lb) and 0.723 lb on compression (FS = 370 lb). These values represent maximum points on the curves supplied by Monroe and were obtained at f_m = 8.5 cycles per second (f_p = 3 cycles per minute).

*FS = full scale.

TEST SETUP

GENERAL LAYOUT

The general layout of the test setup (Fig. 8) was a plywood floor on which a catapult was mounted to give the model its initial velocity. A guide track directed the vehicle along a straight path to the barrier model. Foam-rubber padding was placed beyond the impact point to catch the model after impact and to prevent model damage. Reference markings were placed on the flooring. Two cameras recorded events.

CATAPULT SYSTEM

The catapult was an adaptation of a catapult formerly used to propel seaplane models in water-landing tests. It consists of two concentric cylinders 12-feet long. At each end, "O" rings separate the two cylinders to provide bearing surfaces and air seals. The propelling charge of air was stored in an accumulator in which pressure was controlled by a regulator valve. A solenoid-operated valve controlled the flow of air from the accumulator to the inner (stationary) cylinder. The valve was opened at the start of a run and was automatically closed just before the piston (outer cylinder) reached a point three-quarters along its line of travel. At that time, holes in the outer cylinder passed beyond the inner cylinder's "O" rings, allowing the compressed air to vent into the atmosphere. During the power stroke these same holes allowed the air between the two "O" rings to escape as the cylinder moved forward. Once these holes passed beyond the inner cylinder's "O" rings, an enclosed air space was formed which served as a pneumatic spring to stop the catapult.

The launch rig was attached to the outer cylinder. Safety interlocks made it impossible to operate the catapult until it had been returned to the fully cocked position.

TIMING SYSTEM

Speed was controlled by setting the air pressure in the accumulator. Since it was not possible to predict exact speeds, due to friction in the system and temperature changes during operation, a timer was used to measure the speed of each run. The front roll-bar of the model tripped a contact which started a Hewlett-Packard 526 Time Interval Meter, and the rear roll-bar stopped it. Because the distance between roll-bars was known, model speed could be calculated as

$$V_m = \frac{\ell_m}{t}$$

The equivalent full-scale (prototype) speed V_p (in mph)* can then be calculated from the model speed V_m (in feet per second), as

$$V_p = V_m \sqrt{\lambda}\ \frac{15}{22}$$

For the model used,

$$V_p = \frac{(16.625)(2.83)(15)}{t(12)(22)} = \frac{2.675}{t}$$

where ℓ = length between tripping points on model, in.

λ = scale ratio

t = time, sec

PHOTO SETUP

The camera setup was arranged so that pictures could be taken from an overhead position and from a head-on position. The overhead camera took

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*See Appendix for discussion of modeling considerations.

pictures at 64 pps* which show the complete plan-view trajectory of the model. The camera used for head-on photography was a Hycam high-speed camera capable of speeds of up to 8000 pps, but it was run at 2800, 1400, and 700 pps to give model speeds that could be compared with data obtained in full-size tests in which cameras were operated at the nominal speeds of 1000, 500, and 250 pps.

Because of the high camera speed, it was necessary to illuminate the model and barrier brightly for about 6 feet. To obtain the proper illumination, fifteen Sylvania 750-watt Sun Guns were used. To reduce the amount of heat generated by the lights and absorbed in the floor and barrier it was essential to operate the lights for only a limited time. A magnetic controller was therefore used to turn on the whole light bank at the start of a run and to turn it off as soon as the run was completed.

The cameras were synchronized with the starting mechanism so that they would be up to full speed before model impact on the barrier. A timing pip every 1/120 second was recorded along the edge of the film, as an aid to analysis.

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*Pictures per second.

TEST PROCEDURE

TEST SETUP

The test barrier was aligned with the line of vehicle travel, to give the proper angle of impact, and the whole platform was then rotated so that the barrier was parallel to the sighting line of the high-speed camera. Only minor shifting of the overhead camera and lights was then necessary.

PRE-OPERATION CHECK

Before starting each run the following tasks were performed:

(1) Air was turned on and the pressure-regulator set.

(2) The timer was turned on and checked.

(3) The lights were checked.

(4) The foam padding for catching the model was checked to see that it was in place and not blocking the high-speed camera.

(5) The cameras were plugged in and set.

(6) The cameras were loaded or checked for film.

(7) The proper run-numbers were placed in position.

MODEL TEST RUNS

For each run the catapult was cocked and the model then placed in position.

For low-speed runs (below 25 mph, FS), the procedure below was followed:

(1) The lights were turned on manually.

(2) The catapult was fired manually.

(3) After the cameras stopped (automatically), the lights were turned off manually. (The cameras were started by a relay which operated as soon as the model started to move, if the lights were on.)

(4) Time and run-number were recorded on the data sheet.

(5) The catapult was returned and the model retrieved, inspected, and placed in position for the next run.

(6) After setting new speed, checking cameras for film, and changing run-number, the next test was performed.

For high-speed runs (25 mph and above, FS), the procedure was the same, except that the camera relay was bypassed to permit the cameras to start when the lights were turned on. With lights on, $1\frac{1}{2}$ seconds were allowed for the cameras to reach operating speed and then the catapult was fired manually. Steps 3 through 6 were as described above.

Normally, two runs were obtained on each 100-foot roll of 16-mm film, with the high-speed camera. Approximately twenty runs per 100 feet were obtained with the slower (64 pps) overhead camera.

THEORETICAL ANALYSIS

Before initiation of this program it was known that many full-scale tests on rigid barriers had been conducted by various research groups, and it was understood that a large amount of detailed data had been obtained. It was therefore most disappointing to find, despite rigorous investigation and search on the part of all concerned with this project, such a paucity of full-scale data useful to analysis and model validation. All analysis of the full-scale vehicle's behavior, as it impacts and is redirected by the barrier, is based on the detailed observations of one test recorded in one panning view, taken with a 16-mm camera, and one movie taken with a high-speed camera which appears to have been operated at 1000 pps.[3] The high-speed pictures were taken from a point parallel to the barrier and show the front and part of the undercarriage of the approaching car.

Attempts were therefore made to validate the model by using analytical models. The analytical approach used by Ayre and Abrams at Johns Hopkins University[4] assumed that the model was rigid and had only planar motion. Since the rigid barrier not only deflects the vehicle but also imparts considerable vertical force and roll moment to the vehicle, no planar simulation was considered adequate.

An approach similar to that of Cornell Aeronautical Laboratories[5] was then attempted, although their analysis considered the automobile to be rigid and the barrier to be yielding, while analysis applicable to this study concerns a rigid barrier and a yielding vehicle. To simplify the analysis, minor sheet-metal damage to the front fender was ignored, since the physical model allows no permanent deformation or destruction upon impact. This was justified by reports from New Jersey[6] and by tests conducted at General Motors (with bridge parapets similar in design to the barriers of this study)[2] in which the action of the vehicle when striking the barrier was similar in all instances, whether or not minor sheet-metal damage occurred.

Because of the many degrees of freedom inherent in the problem, equations became unwieldy. Further complications arose in efforts to

describe the dynamics of the front suspension. Under these circumstances, a decision was made to defer any analytical work until such time as appropriate suspension data and full-scale test results were available.

RESULTS

The major results of the tests, as discussed in this section, are also recorded in the film which is a part of this report. The accompanying table (p. 20) is a tabulation of some of the test results. In the table, the first column shows test number; tests with numbers that have asterisks are depicted in the film (already submitted to the New Jersey Department of Transportation). The second column indicates the barrier under test: "GM" denotes the barrier shown in Figure 7, "NJ" the one in Figure 6. Column 3 indicates the model vehicle: the fully suspended model is shown in Figure 3, the semi-suspended model in Figure 2, and the rigid-frame in Figure 1. The impact angle of the fourth column is the angle between the catapult and the barrier (see Fig. 8). Velocity, in the fifth column, is the velocity registered at the timer station (also shown in Fig. 8).

The sixth and seventh columns are intended to represent the actions of the model after impact. In general, the car, after impact, reached a steady-state condition within a distance of two car lengths from the point of collision. The sixth column shows maximum lateral displacement of any point on the vehicle within those two car lengths, in feet, full scale (0.00 means the model was snug against the barrier; 1.00 means that some part of the model extended as much as 1 foot farther from the barrier than the width of the vehicle). In no case did the model leap the barrier. The seventh column shows the attitude of the vehicle after it had traveled two car lengths from impact. A negative sign means that the model was headed back toward the barrier, a positive one that the model was headed away. In the former case the figure in Column 6 is the maximum excursion; in the latter, the excursion would continue to increase indefinitely unless the driver made a correction. With the accuracy of the measurement technique established as better then 0.5 mph, there was no discernible difference in model speed after impact.

Since existing full-scale data were inadequate for purposes of comparison, no conclusion can be drawn -- from the model-test results alone --

which would bear upon the accuracy with which the model simulated the prototype. Nor can more extensive experimental study, with many different models and barriers, be justified until adequate full-scale data are available and the model simulation can be established as accurate. However, certain qualitative observations may be made regarding the performance of the experimental model as compared with the performance of the prototype in the one test for which information on the prototype is available.

In a typical model test, the model did not behave as a prototype under test might have been expected to behave. The problem was to determine just which discrepancies were due to the properties of the model as such (model distortion) and which were attributable to characteristics which were not properly modeled (body twisting, steering slop and deflection, tire properties, roll moment of inertia, yaw moment of inertia, sprung-to-unsprung-mass ratio, etc.).

Comparisons of the film records of the model tests with the film of the General Motors full-size tests[3] show that model behavior compares favorably at speeds approximating one-half the full-size speed. Qualitative analysis of the fully suspended model (at 23 mph FS, Fig. 10) shows good correlation with the prototype (50 mph, Fig. 9). At higher speeds the model's behavior is characterized by exaggerated climbing and rolling tendencies.

In the high-speed films of the model, it is apparent that when the suspension bottoms there is a definite second impulse to the chassis. This impulse causes the whole vehicle to rise higher and start to roll. Such a second impulse was not observed in the full-size test. In fact, it is difficult to determine, by observing the behavior of the full-scale car, whether the suspension even bottoms at all.

The coefficient of friction between the model tire and road surface was approximately 0.8, a value to be expected on a concrete surface. The full-scale tests, however, were conducted on packed dirt and gravel, hence the friction coefficient was probably much lower. In the model tests, the higher frictional force and the tendency of the wheels to keep rolling straight ahead forced the model to attempt a longer climb up the barrier.

The rigidity of the model system was further compounded by the stiffness of the tires. Delays in procuring material with the proper density

made it impossible to scale the tires to the proper load-deflection curve. The model tires deflected at a rate of 0.029 lb/in., which is equivalent to 2200 lb/in. full scale. A typical figure for 750-14 2-ply tires at 24 pounds per square inch is 1100 lb/in. Thus the model tire would absorb less of the energy of impact, and this would cause the model to ride still higher on the barrier.

In model tests with the General Motors barrier, the model rolled in a direction away from the barrier (Fig. 11), as did the prototype (Fig. 9). It was observed, however, that in model tests against the New Jersey barrier the vehicle's behavior differed. The model usually left the area of impact in an almost horizontal attitude, and if there was a tendency to roll it was in a direction toward the barrier (Fig. 12). Though this is not conclusive, it does at least show that the model is sensitive to relatively small changes in barrier configuration, since the differences between the New Jersey barrier and the General Motors barrier are quite small (compare the cross sections in Figs. 6 and 7). The lack of complete model validation makes it impossible at this time to extrapolate information from model tests which would support any conclusion that a full-size vehicle would react in exactly the same manner on impact against the New Jersey barrier.

Perhaps most significant is the fact that in no case of speeds up to 60 mph (full size) and impact angles up to 16 degrees did the model jump either of the 32-inch (full size) barriers. Since the characteristics of the model appear to be more "lively" than those of the prototype, and since research indicates that over 90 percent of road departures occur at less than 7 degrees,[7] the 32-inch barrier appears to fulfill its intended roll of separating the opposing streams of passenger-car traffic.

SUMMARY OF TEST RESULTS

Run No.	Barrier Type	Model Suspension	Impact Angle (deg)	Velocity mph (full scale)	Max. Lateral Displ. Within Two Car Lengths (ft, full scale)	Departure Angle at Two Car Lengths (deg)	Remarks
1	GM	Fully suspended	12	18.5	-	-	Failure
2*	GM	"	12	23.8	0.00	-4	Model snubbing barrier
3*	GM	"	12	30.8	0.55	0	
4*	GM	"	12	33.8	1.06	-1	
5*	GM	"	12	43.0	1.36	+4	Model still in air at two car lengths; landed on side
6	GM	"	12	48.5	1.61	+3	Model still in air at two car lengths; landed on side
7	GM	"	12	50.5	1.87	+3	Model still in air at two car lengths; landed on top
8	GM	"	12	50.5	1.77	+2	Model still in air at two car lengths; landed on top
9	-	-	-	-	-	-	No run
10	GM	Semi-suspended	12	39.6	2.32	+5	Model still in air; large roll angle
11*	GM	"	12	37.5	2.27	+5	Model still in air; large roll angle
12*	GM	Rigid frame	12	27.8	0.91	+3	Model still in air; large roll angle

SUMMARY OF TEST RESULTS (Cont'd)

Run No.	Barrier Type	Model Suspension	Impact Angle (deg)	Velocity mph (full scale)	Max. Lateral Displ. Within Two Car Lengths (ft, full scale)	Departure Angle at Two Car Lengths (deg)	Remarks
13	GM	-	-	-	-	-	No run
14	GM	Rigid frame	12	37.5	1.21	+8	Model still in air
15	GM	Semi-suspended	12	44.5	1.41	+7.5	Model still in air
16	-	-	12	-	-	-	No run
17*	NJ	Fully suspended	12	40.5	0.35	-5	Model still in air
18	NJ	"	12	35.0	0.10	-2	Model continued to leave barrier at about 2°
19*	NJ	"	12	35.6	0.30	-6.5	
20*	NJ	"	12	49.5	0.60	-4	Model still in air
21	-	-	-	-	-	-	No run
22*	NJ	"	8	37.6	0.65	-2	
23*	NJ	"	8	47.7	0.85	-5	Model still in air
24	NJ	"	8	50.5	1.01	-1.5	Model still in air
25*	NJ	"	8	50.5	0.96	-3.5	Model still in air
26	NJ	"	16	40.0	1.01	-2	Model headed toward barrier after landing

SUMMARY OF TEST RESULTS (Cont'd)

Run No.	Barrier Type	Model Suspension	Impact Angle (deg)	Velocity mph (full scale)	Max. Lateral Displ. Within Two Car Lengths (ft, full scale)	Departure Angle at Two Car Lengths (deg)	Remarks
27*	NJ	Fully suspended	16	40.0	0.20	-4	
28	NJ	"	16	39.5	0.30	-6	Model landed on right wheels; departed parallel to barrier
29*	NJ	"	16	38.5	0.76	-4	Model still in air
30	NJ	"	16	44.5	0.81	-6	Model still in air
31	NJ	"	16	44.5	0.86	-3	Model still in air

*Signifies runs which are on the film that accompanies this report.

CONCLUSIONS

(1) The use of models in simulating dynamic vehicle behavior is feasible. (Though not conclusively proven in this program, enough qualitative similarity between model performance and prototype behavior was observed to warrant the conclusion that model simulation can eventually be obtained.)

(2) The rapidity and ease with which many tests were conducted demonstrate some of the outstanding advantages of model-testing over prototype-testing, once model simulation is obtained.

(3) Model simulation cannot be quantitatively established until enough well-instrumented full-scale tests have been conducted and their results made available for comparison.

(4) Further model-testing is not justified until adequate full-scale data are available.

RECOMMENDATIONS

(1) Instrumented full-scale tests should be conducted before further model work is attempted.

(2) The model should be further tuned, to obtain reliable model simulation. To do this, data from the above-mentioned full-scale tests should be used.

(3) With the validated model, tests should be conducted against various barriers of practical size and shape, to determine precise vehicle-barrier interaction. Rigid-barrier-design data should be developed from such a study.

(4) Once rigid-barrier simulation is established, simulation could be extended to include the impact phenomenon in the case of the vehicle and a flexible barrier.

ACKNOWLEDGEMENTS

The authors wish to thank Messrs. Louis C. Lundstrum and Paul C. Skeels of General Motors Proving Ground, Mr. W. W. Higginbotham of the Monroe Auto Equipment Company, Messrs. C. I. Carr and Dan Elliot of Uniroyal (the United Stated Rubber Company), and Mr. Malcolm D. Graham of the New York Department of Public Works, whose assistance and cooperation were necessary to the collection of technical material and information.

Thanks are due also to Mr. Irmin O. Kamm and Mr. M. Peter Jurkat, for advice and suggestions in various phases of the project, and to Mr. Herant Deroian for assistance with photographic work.

EPILOGUE

All is not lost! After completion of this report and just before publication, word was received that -- as a result of the efforts of the Bureau of Public Roads -- the Department of Highways of the State of California has agreed to include, in their planned full-scale barrier test program, tests appropriate for comparison with the model program described here.

APPENDIX

Modeling Considerations

The following modeling considerations apply to the program described in this report.

(1) Geometric simulation is represented by

$$\ell_p = \lambda \ell_m$$

where every dimension is greater in the prototype by the factor λ .

(2) If the density of the model and prototype are to be the same (not necessary in this simulation, but convenient), then

$$\frac{W_p}{\ell_p^3} = \frac{W_m}{\ell_m^3}$$

$$W_p = W_m \frac{\ell_p^3}{\ell_m^3} = \lambda^3 W_m$$

Therefore, weights on the prototype are greater by the factor λ^3 .

(3) Since gravity is constant,

$$g_p = g_m$$

(4) For masses,

$$W = Mg$$

$$\therefore \quad M_p = \lambda^3 M_m$$

(5) If the horizontal forces are to be compatible with the vertical forces, then

$$F_p = \lambda^3 F_m$$

(6) From Newton's law,

$$F_p = M_p a_p = \lambda^3 F_m = \lambda^3 (M_m a_m)$$

$$\therefore \quad a_p = \lambda^3 \left(\frac{M_m}{M_p}\right) a_m$$

$$a_p = \lambda^3 \left(\frac{M_m}{\lambda^3 M_m}\right) a_m$$

$$a_p = a_m$$

Therefore, accelerations in both model and prototype will be the same.

(7) Since $a = \ell/t^2$,

$$\frac{\ell_p}{t_p^2} = \frac{\ell_m}{t_m^2}$$

$$t_p^2 = \frac{\ell_p}{\ell_m} t_m^2 = \lambda t_m^2$$

$$t_p = \sqrt{\lambda}\, t_m$$

Time will go by faster in the model.

(8) For velocities, $V = \ell/t$, and

$$V_p = \frac{\ell_p}{t_p} = \frac{\lambda \ell_m}{\sqrt{\lambda} t_m} = \sqrt{\lambda}\, V_m$$

Speeds will be slower in the model.

(9) For springs, $k = F/\ell$, and

$$k_p = \frac{F_p}{\ell_p} = \frac{\lambda^3 F_m}{\lambda \ell_m} = \lambda^2 k_m$$

Springs should be much weaker in the model.

(10) For shock absorbers, $c = \frac{Ft}{\ell}$, and

$$c_p = \frac{F_p t_p}{\ell_p} = \frac{\lambda^3 F_m \sqrt{\lambda} t_m}{\lambda \ell_m} = \lambda^{5/2} c_m$$

Shocks also will be weaker for the model.

(11) For camera speeds, $pps = 1/t$, and

$$pps_p = \frac{1}{t_p} = \frac{1}{\sqrt{\lambda} t_m} = \frac{1}{\sqrt{\lambda}} pps_m$$

To record the event properly the camera used in taking the pictures of the model tests should be faster than the camera used in photographing the prototype.

(12) For moment of inertia, $I = F\ell^2$, and

$$I_p = F_p \ell_p^2 = \lambda^3 F_m \lambda^2 \ell_m^2 = \lambda^5 I_m$$

(13) For tire deflection, $\delta = F/\ell$, and

$$\delta_p = \frac{F_p}{\ell_p} = \frac{\lambda^3 F_m}{\lambda \ell_m} = \lambda^2 \delta_m$$

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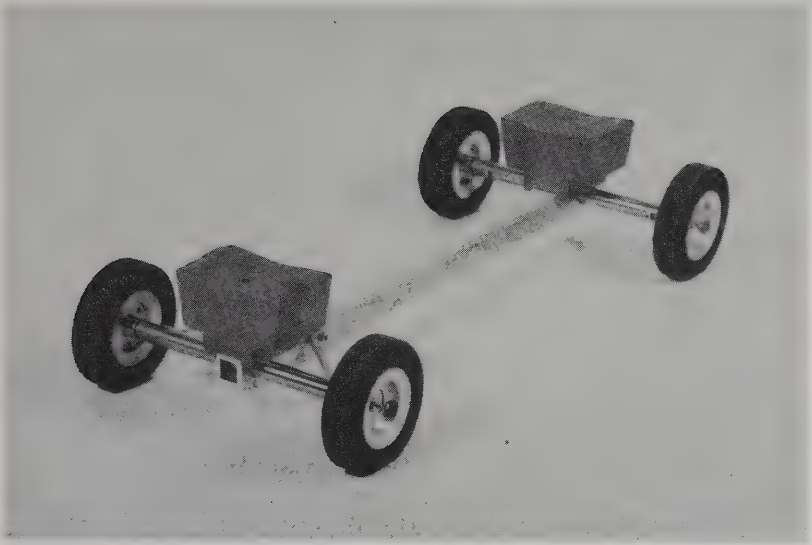

FIGURE 1. RIGID MODEL

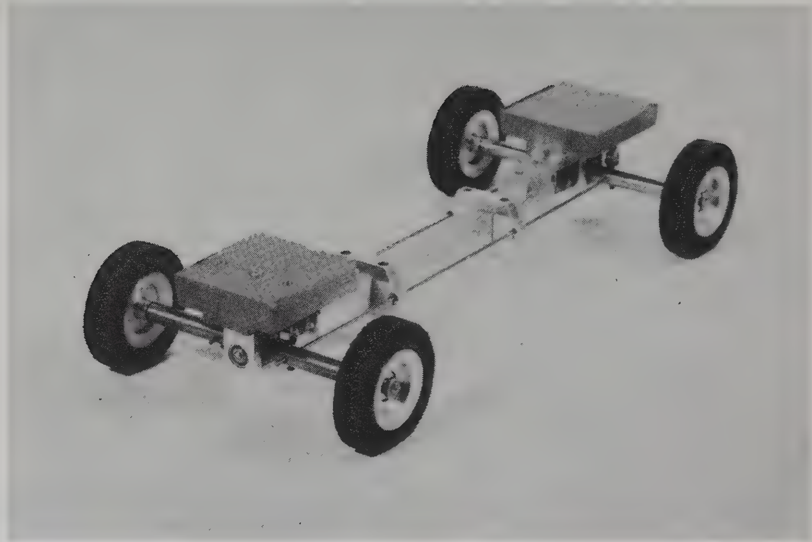

FIGURE 2. SEMI-SUSPENDED MODEL

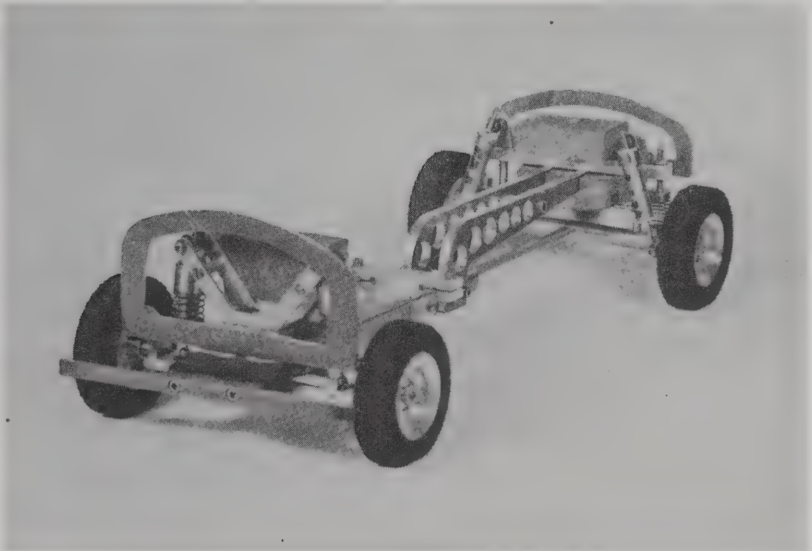

FIGURE 3. FULLY-SUSPENDED MODEL

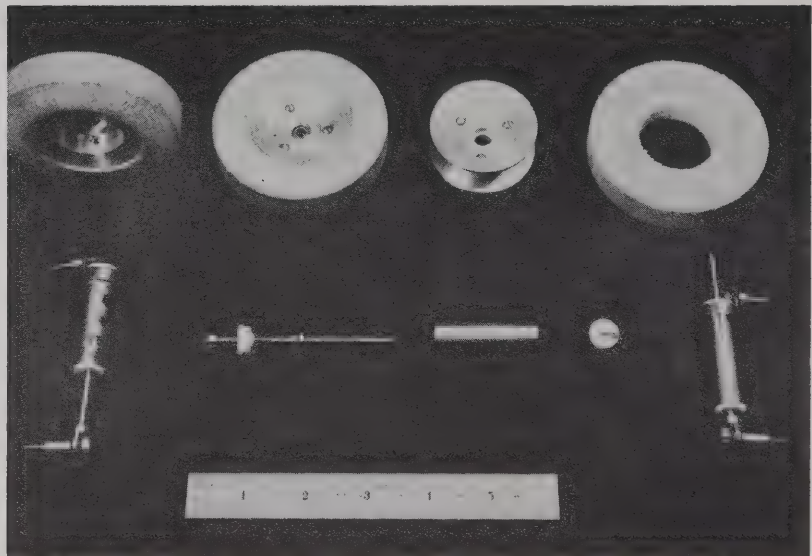

FIGURE 4. SHOCK ABSORBERS AND WHEELS

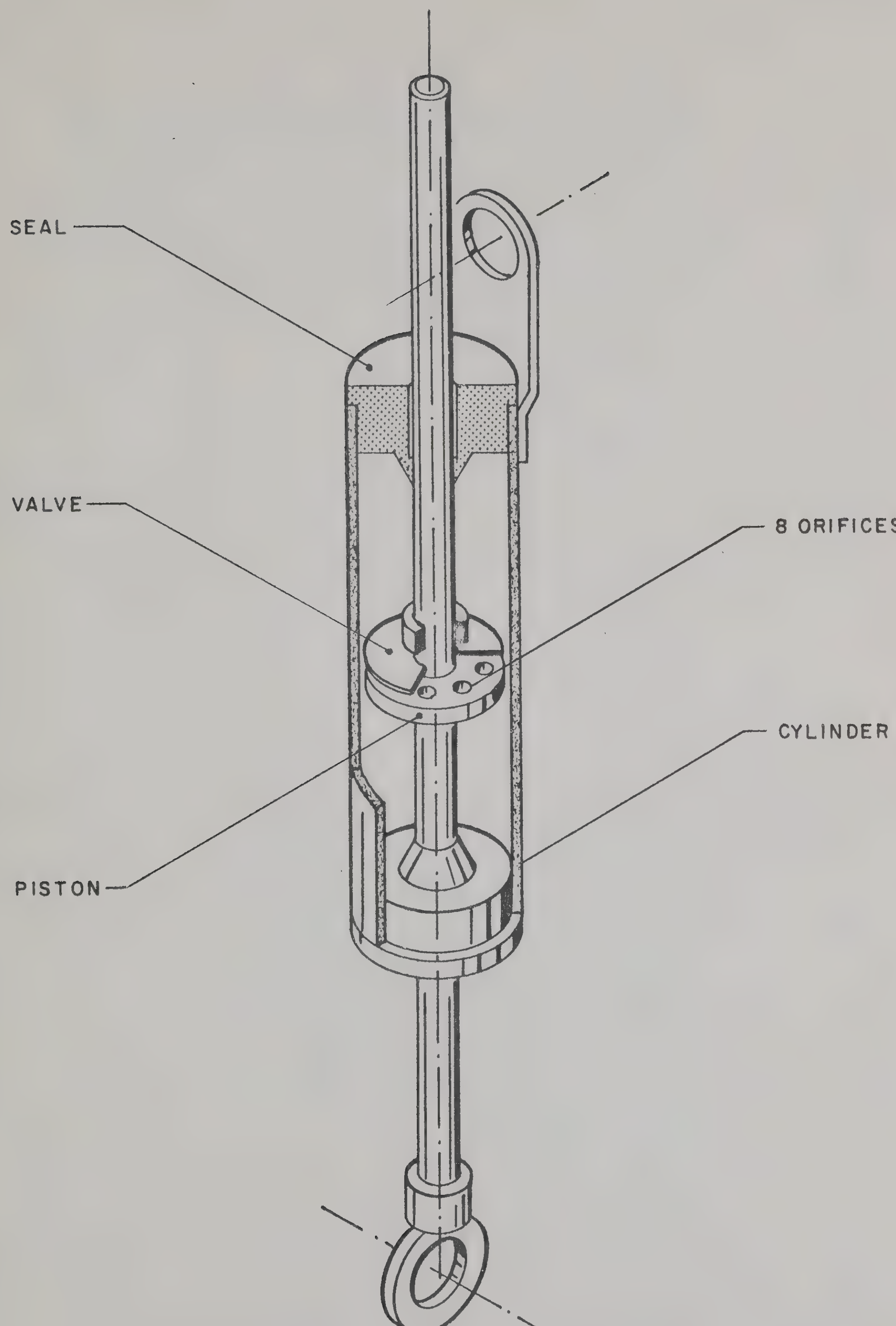

FIGURE 5. SHOCK-ABSORBER ASSEMBLY

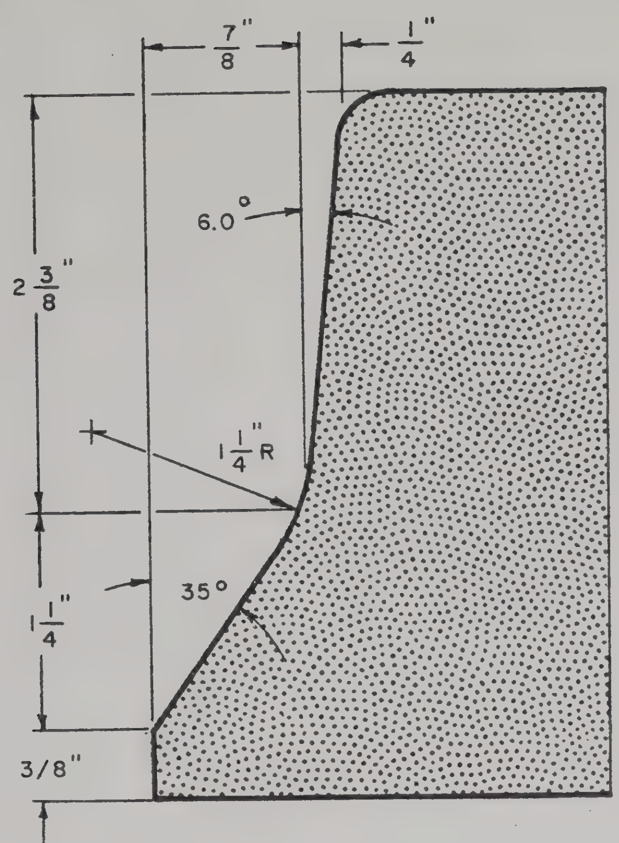

FIGURE 6. SCALED DIMENSIONS OF THE MODIFIED NEW JERSEY BARRIER

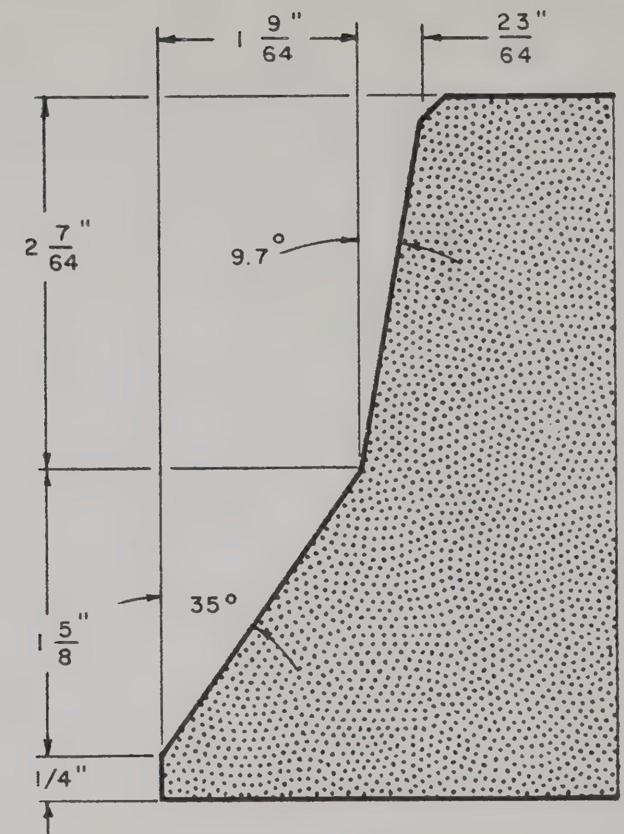

FIGURE 7. SCALED DIMENSIONS OF THE GENERAL MOTORS BARRIER

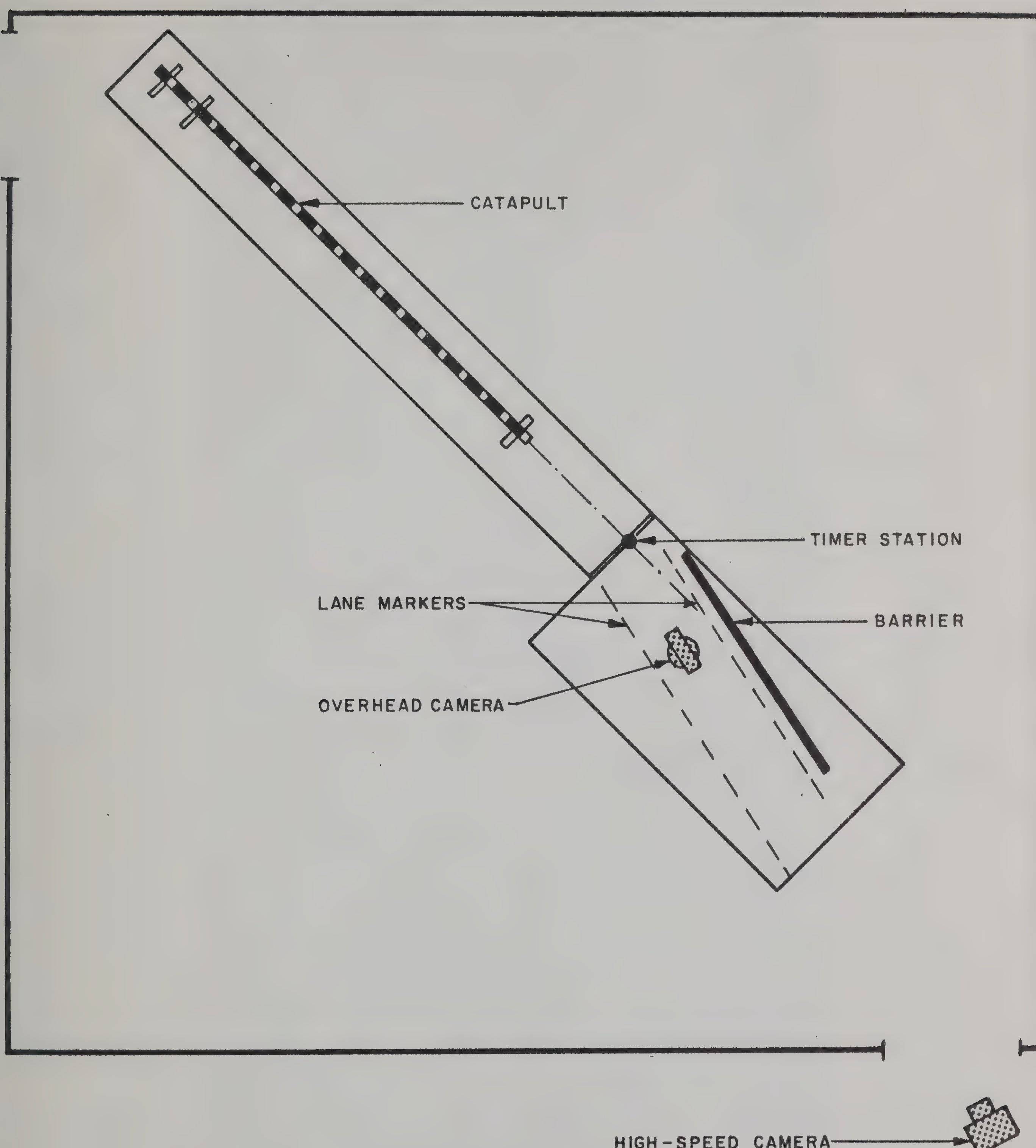

FIGURE 8. TEST LAYOUT SHOWING CATAPULT, BARRIER, AND CAMERAS

FIGURE 9. HIGH-SPEED PHOTOS, GENERAL MOTORS BARRIER

Approx. 50 mph, 12° Angle of Impact

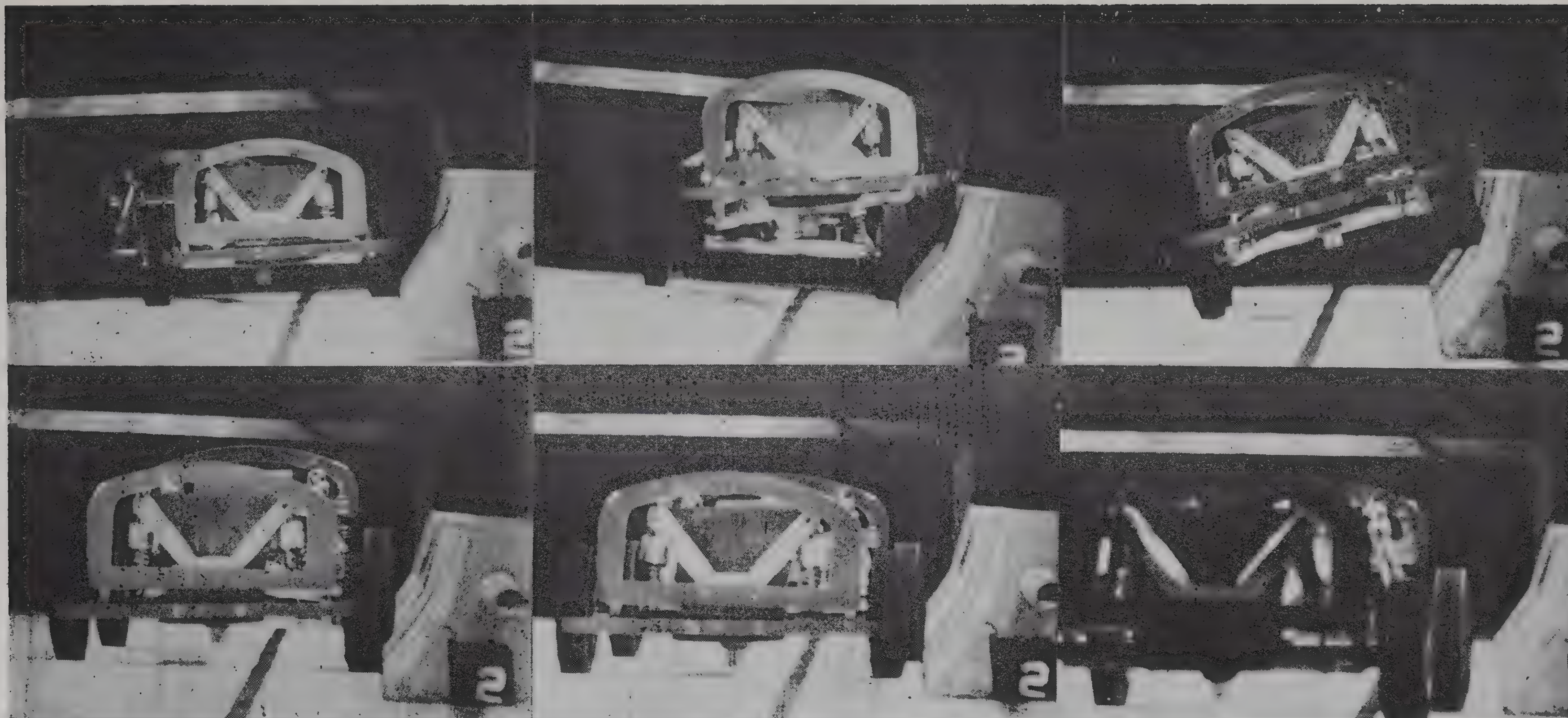

FIGURE 10. HIGH SPEED PHOTOS - DAVIDSON LAB MODEL/BARRIER STUDY
23.8 MPH - 12° ANGLE OF IMPACT (GM BARRIER)

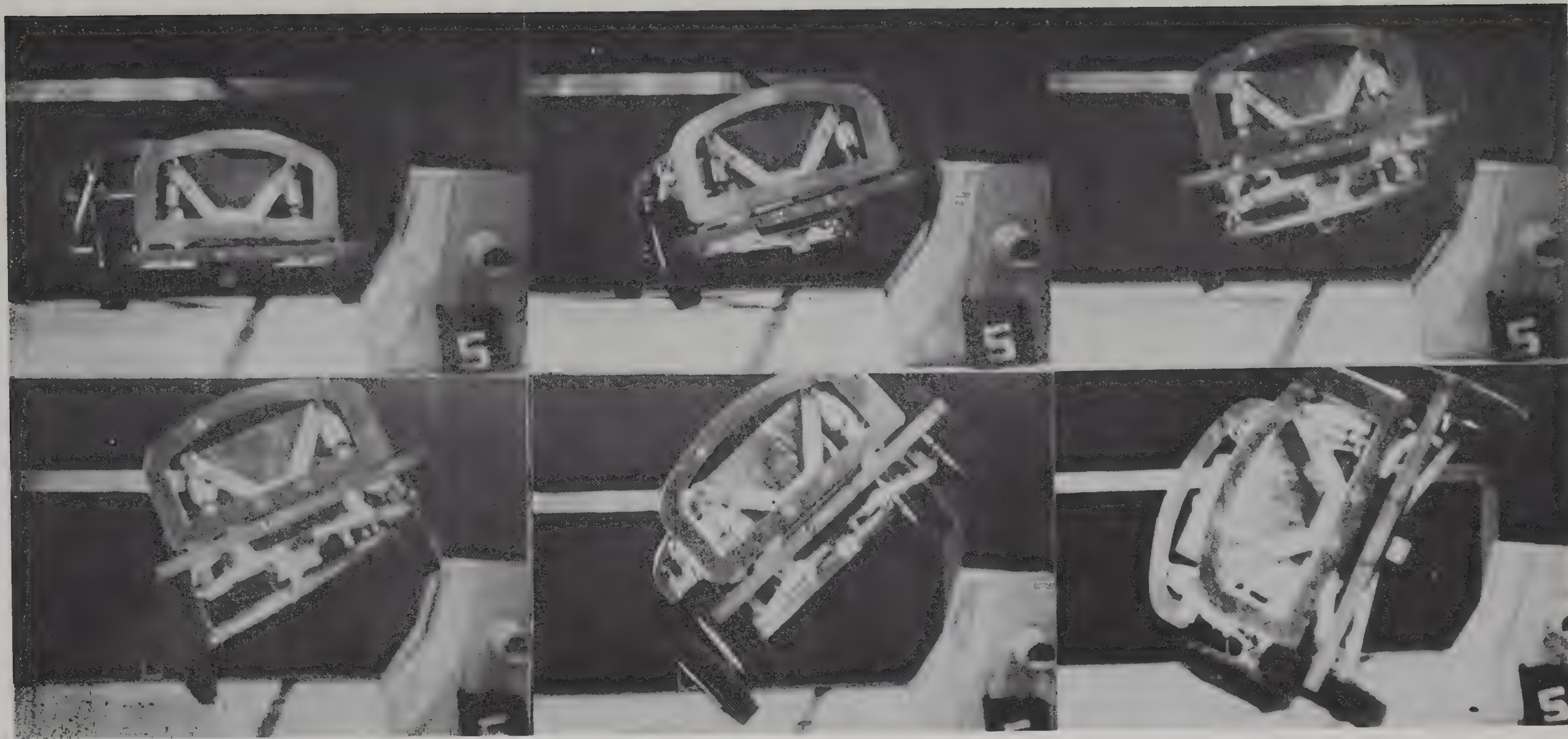

FIGURE 11. HIGH SPEED PHOTOS - DAVIDSON LAB MODEL/BARRIER STUDY
43.0 MPH - 12° ANGLE OF IMPACT (GM BARRIER)

FIGURE 12. HIGH SPEED PHOTOS - DAVIDSON LAB MODEL/BARRIER STUDY
40.5 MPH - 12° ANGLE OF IMPACT (N.J. BARRIER)

DAVIDSON LABORATORY, Stevens Inst. of Tech.
Hoboken, N. J.

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